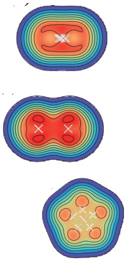
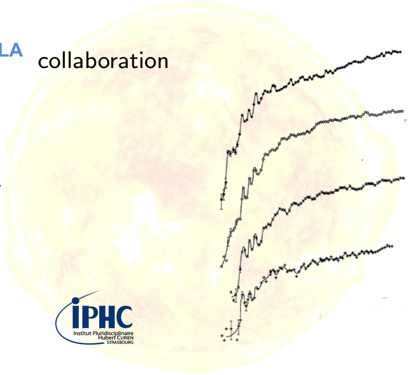
Nuclear Astrophysics in France and TransNational Access: $^{12}C+^{12}C$ at Deep sub Barrier Energies with STELLA



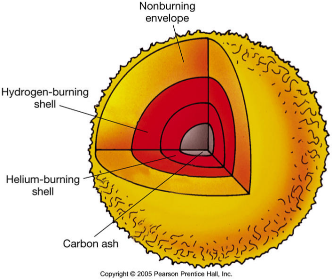
Marcel Heine for the STELLA collaboration

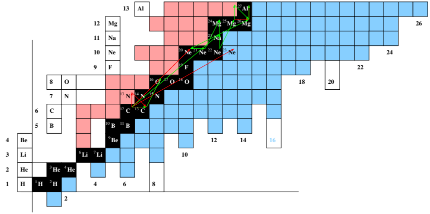
IPHC/CNRS

May 28, 2024



Advanced Burning in Massive Stars: Carbon Burning



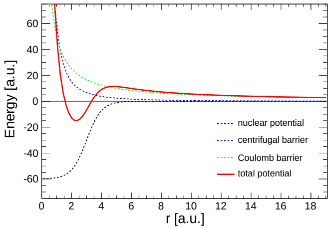


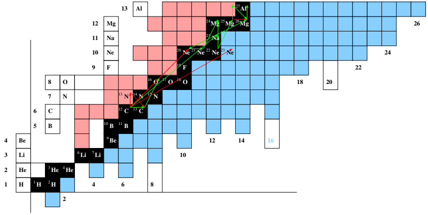
from A. Chieffi *et al.*, APJ **502** (1998), 737

$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow ^{24}\mathrm{Mg}^* \rightarrow ^{24}\mathrm{Mg} + \gamma$$
$$\rightarrow ^{23}\mathrm{Mg} + \mathrm{n}$$
$$\rightarrow ^{23}\mathrm{Na} + \mathrm{p}$$
$$\rightarrow ^{20}\mathrm{Ne} + \alpha$$

$$M = (10\ldots60)\ M_\odot$$
$$T = (0.5\ldots1)\ \mathrm{GK}$$
$$\rho = (10^4\ldots10^5)\ \mathrm{g/cm^3}$$

Advanced Burning in Massive Stars: Carbon Burning





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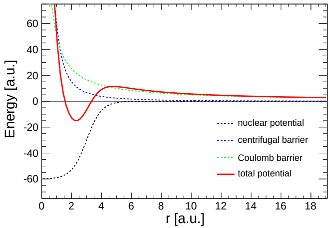
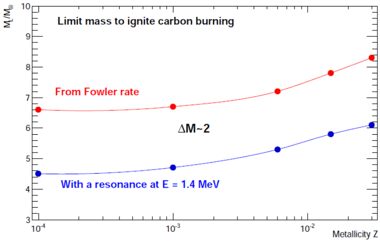
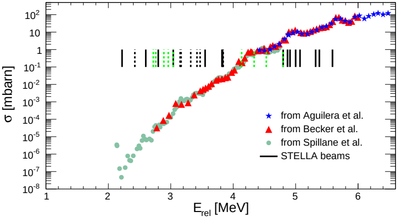


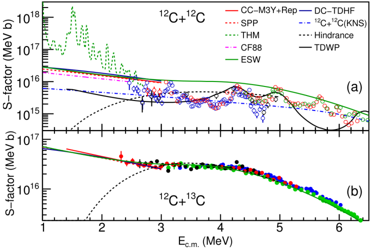


from: O. Straniero *et al.*, JPC Ser. **665** (2016), 012008

- comprehensive direct data
- gamma: Aguilera *et al.*, Spillane *et al.*
- particle: Becker *et al.*
- thin and thick target

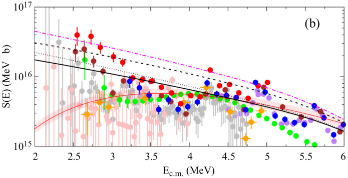


- oscillating excitation function
- region systematically below CF88
- vanishing cross sections ($\leq$ nbarn)
- direct & indirect measurements

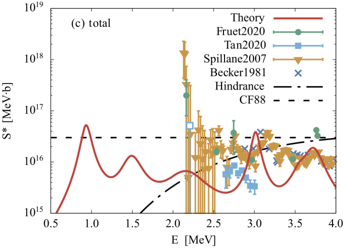


N.T. Zhang *et al.* PLB **801**, 135170 (2020)

- extrapolations, calculations with huge scatter towards low energy



K. Godbey *et al.* PRC **100**, 024619 (2020)

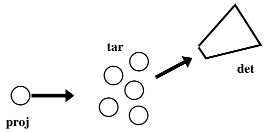


Y. Tanigushi & M. Kimura PLB **823**, 136790 (2021)

- alpha-conjugate system: resonances (THM, el. α scattering @ iThemba)
- low density of states in ^{24}Mg: hindrance (below averaging CF88)
- ^{12}C are stiff nuclei:

  generally low cross sections

  broad hindrance maximum
- stellar site: deep sub Coulomb barrier: exponential drop of cross sections

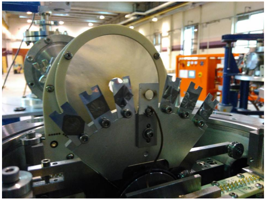


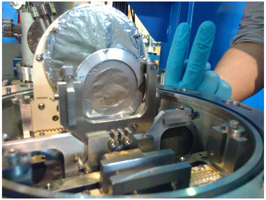
1. beam intensities of a few pμA
2. data taking for weeks
3. γ-particle coincidences
4. low counting statistics analysis

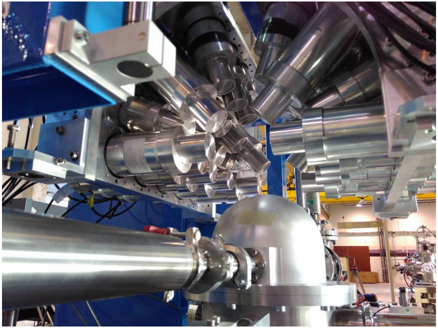
- data/results from $^{12}C+^{12}C$ measurements @ Andromède, IJCLab Orsay

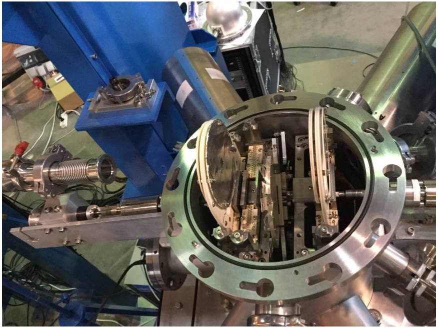
The STELlar LAboratory Setup

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{23}\mathrm{Na} + \mathrm{p} + \gamma$$
$$\rightarrow {}^{20}\mathrm{Ne} + \alpha + \gamma$$

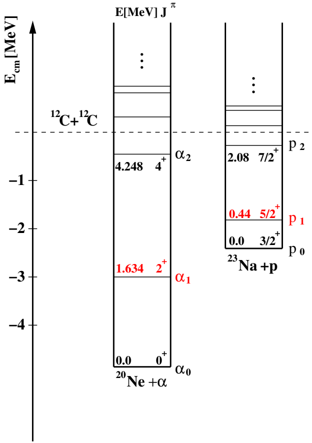




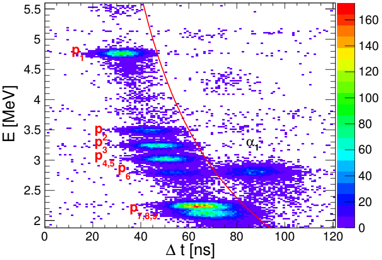




- synchronization of 1 GHz gamma DAQ and 125 MHz particle DAQ
- energy-deposition in silicon substrate: triggering on pulse shape



- timing gates $\sigma \sim$15 ns
- proton-α separation



M. Heine *et al.*, NIM A **903** (2018), 1

- synchronization of 1 GHz gamma DAQ and 125 MHz particle DAQ
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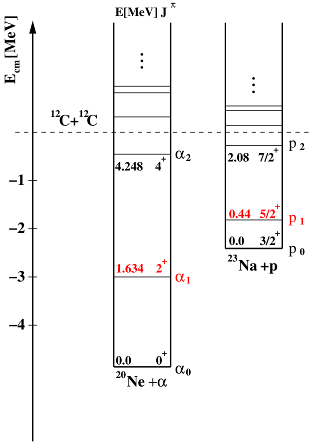
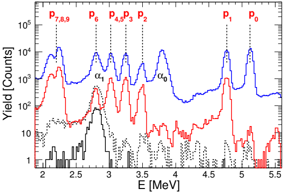
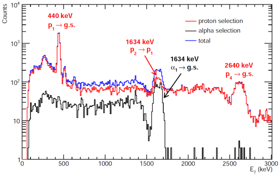
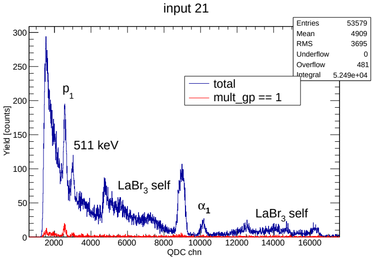




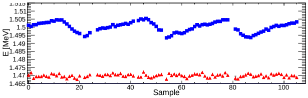


G. Fruet, PhD thesis, Université de Strasbourg (2018)

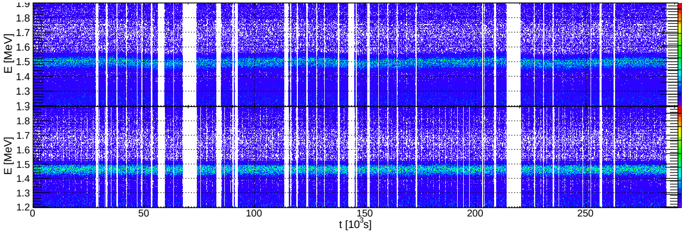
Analysis Technique



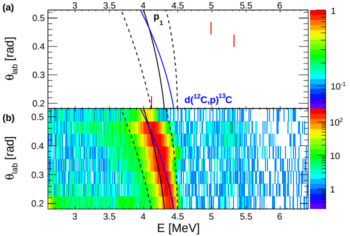
- ~ 3 days of data; 45 min blocks
- drift of 1.47 MeV line: 1.5 keV
- since calibration: 30 keV



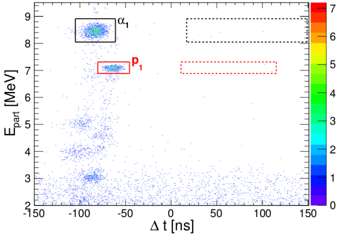
M. Heine *et al.*, NIM A **903** (2018), 1



Analysis Technique

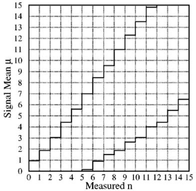


G. Fruet *et al.*, PRL **124** (2020), 192701



M. Heine *et al.*, EPJ Web Conf **260** (2022), 01004

- avoid negative physics counts:



$$n = 1\ (\text{observed}),\ b = 1\ (\text{background}),\ \mu = n - b$$

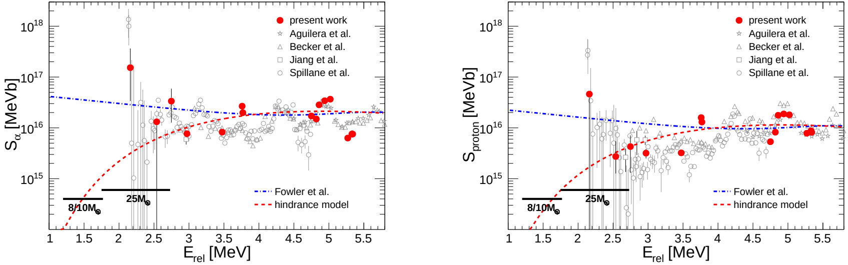
$$\frac{\Delta\mu}{\mu} = \sqrt{\left(\frac{\Delta n}{n}\right)^2 + \left(\frac{\Delta b}{b}\right)^2}\ \text{N.A.N.}$$

$$n = 1, b = 1 \to \mu \in [0.00, 1.75]$$

$$n = 2, b = 2 \to \mu \in [0.00, 2.25]$$

G.F. Feldman & R.D. Cousins, PRD **57** (1998), 3873

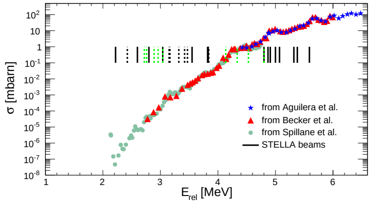
- lowest energies:
  - weeks of data acquisition with pμA ^{12}C beam
  - measurement p_1 and α_1



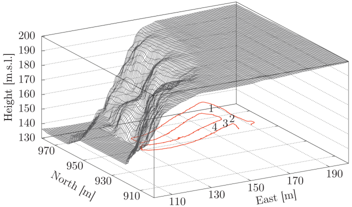
G. Fruet *et al.*, PRL **124** (2020), 192701

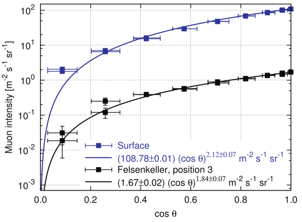
1. moderate sub-barrier regime above $E_{rel} = 4.5$ MeV
2. deep-sub-barrier regime from $E_{rel} = 2.5$ MeV to 4 MeV
   - observation of hindrance
3. 25 $M_\odot$ Gamow window below $E_{rel} = 2.5$ MeV
   - change in the fusion mechanism

- extend direct coincidence measurements
- increase overlap with indirect data



- assessment of background sources
- muon characterisation at Felsenkeller
- muon veto during data acquisition





F. Ludwig *et al.*, AP **112** (2019), 24–34

STELLA at the Felsenkeller Shallow Underground Laboratory

PHYSICAL REVIEW LETTERS **124,** 192701 (2020)

Advances in the Direct Study of Carbon Burning in Massive Stars

G. Fruet,[1,2] S. Courtin,[1,2,3,*] M. Heine,[1,2,†] D. G. Jenkins,[4] P. Adsley,[5] A. Brown,[4] R. Canavan,[6,7] W. N. Catford,[6] E. Charon,[8] D. Curien,[1,2] S. Della Negra,[5] J. Duprat,[9] F. Hammache,[5] J. Lesrel,[5] G. Lotay,[6] A. Meyer,[5] D. Montanari,[1,2,3] L. Morris,[4] M. Moukaddam,[6] J. Nippert,[1,2] Zs. Podolyák,[6] P. H. Regan,[6,7] I. Ribaud,[5] M. Richer,[1,2] M. Rudigier,[6] R. Shearman,[6,7] N. de Séréville,[5] and C. Stodel[10]

PHYSICAL REVIEW LETTERS **129,** 102701 (2022)

Extending the Hoyle-State Paradigm to $^{12}C + ^{12}C$ Fusion

P. Adsley,[1,2,*,†] M. Heine,[3,4] D. G. Jenkins,[5,6,7] S. Courtin,[3,4,6] R. Neveling,[2] J. W. Brümmer,[8] L. M. Donaldson,[2] N. Y. Kheswa,[2] K. C. W. Li,[8] D. J. Marín-Lámbarri,[2,7,9] P. Z. Mabika,[7] P. Papka,[2,8] L. Pellegri,[1,2] V. Pesudo,[2,7,10] B. Rebeiro,[7] F. D. Smit,[2] and W. Yahia-Cherif[11]

A&A 660, A47 (2022)
https://doi.org/10.1051/0004-6361/202141858

Astronomy & Astrophysics

A new $^{12}C + ^{12}C$ nuclear reaction rate: Impact on stellar evolution

E. Monpribat[1], S. Martinet[2], S. Courtin[1,3], M. Heine[1], S. Ekström[2], D. G. Jenkins[3,4], A. Choplin[5], P. Adsley[6,7], D. Curien[1], M. Moukaddam[1], J. Nippert[1], S. Tsiatsiou[2], and G. Meynet[2]

+ E. Bella, A. Bonhomme, P. Cotte, G. Häffner, T. Dumont, L. Morrison, G. Vega, J. Vesić